Task Team on Climate Reanalysis (TT-CliRen)
Geneva, Switzerland, 10 to 12 October 2023

WEATHER CLIMATE WATER
TEMPS CLIMAT EAU

Agenda 5.3

Ocean State Estimation at NASA in Support of Climate Research

10 October 2023

Patrick Heimbach, Ian Fenty & Co-authors

Estimating the Circulation and Climate of the Ocean

NASA/ECCO – https://ecco-group.org

WMO OMM
World Meteorological Organization
Organisation météorologique mondiale

An era of unprecedented Earth observations

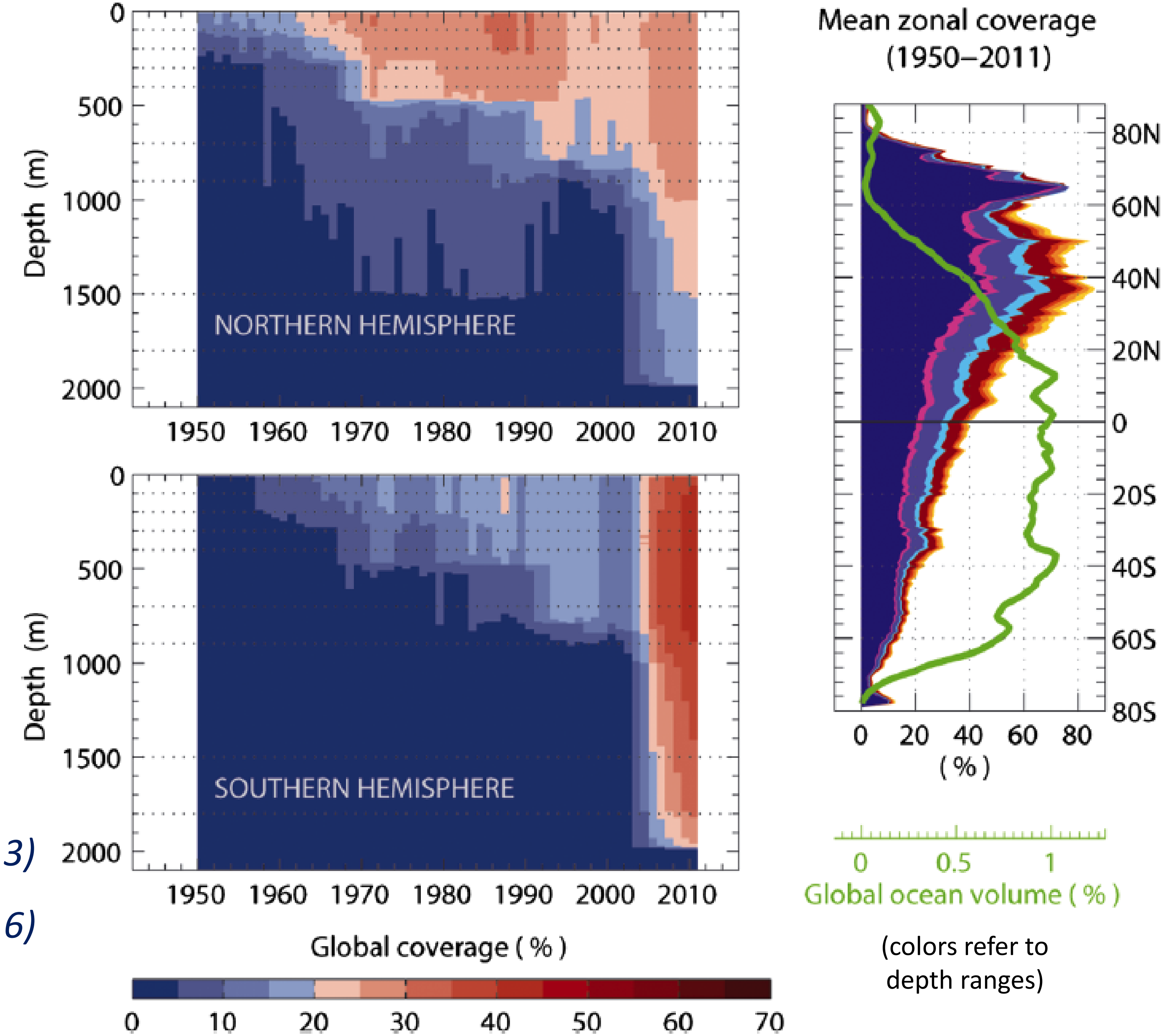
Oceanography remains a ***sparse data*** problem observationally…

Observational sampling for ocean temperature in the upper 2000 m 1950 – 2010

(recall: mean ocean depth ~ 3900 m)

Abraham et al., Rev. Geophys. (2013)

Wunsch (2016)



(colors refer to depth ranges)

Two incomplete knowledge reservoirs:

A global ocean observing system …
… that is eclectic, sparse, and heterogenous

Numerical models …
… that require uncertain initial / boundary conditions and model parameters

- Can we **optimally combine** these two incomplete knowledge reservoirs?
- Can we do so in a manner that provides **useful for climate analysis**?
  - enable causal, dynamical attribution
  - detect small, residual signals
  - avoid artificial trends
- Can we provide **measures of uncertainties** with these?
- Can we use simulation to **inform efficient observing strategies for climate**?

Estimating the Circulation and Climate of the Ocean

https://ecco-group.org

The "Estimating the Circulation and Climate of the Ocean" (ECCO) consortium makes the best possible estimates of ocean circulation and its role in climate. Our solutions combine **state-of-the-art ocean circulation models** with global ocean data sets.

What sets us apart from other models? We reproduce observations in a **physically and statistically consistent manner**. Over a thousand ECCO-related publications attest to our products' value for understanding changes in the ocean – including sea level rise, sea ice loss, El Niño events, and the cycling of water and carbon.

WHAT'S NEW

- Augmenting a Sea of Data With Dynamics [see all updates]
- Wind at Work [see all featured publications]
- See how ECCO Supports NASA Science
- ECCO at PO.DAAC

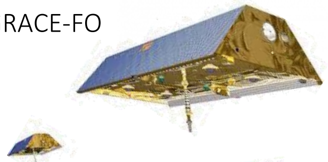
View X Posts by OceanECCO »

ECCO state estimates are *multi-platform, multi-instrument, multi-variable* synthesis products that integrate ocean and ice observations and models

Sentinel-6
Michael Freilich

TOPEX/Poseidon

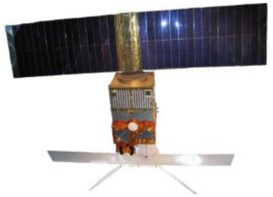
GRACE
GRACE-FO



JASON 1,2, 3

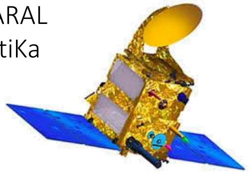
Aquarius
SAC-D

ERS 1,2

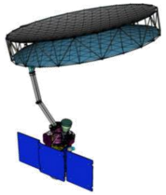


SMOS

SARAL
AltiKa

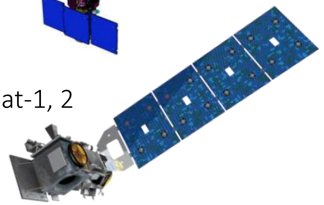


SMAP



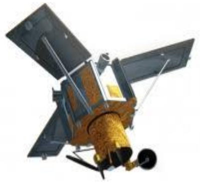
Cryosat-2

ICESat-1, 2

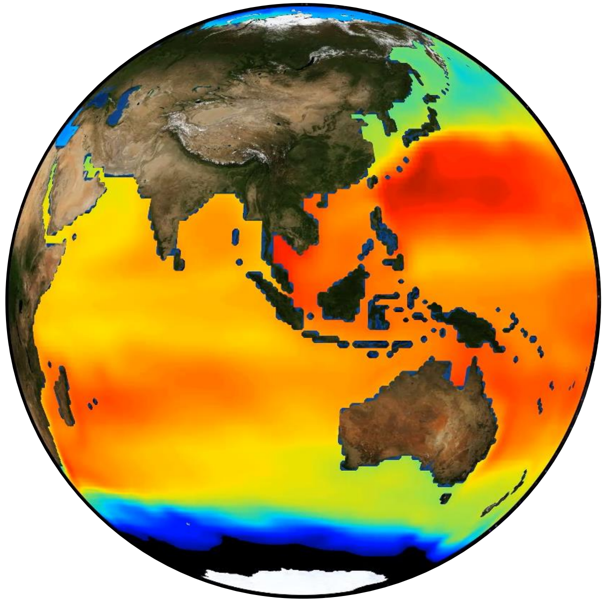


DMSP SMMR,
SSM/I SSMIS

AVHRR



Coupled Ocean/Sea-ice
General Circulation Model



$$
\frac{\partial \boldsymbol{v}}{\partial t} + (f+\zeta)\hat{\boldsymbol{k}} \times \boldsymbol{v} + \nabla_{z^*}\mathrm{KE} + w\frac{\partial \boldsymbol{v}}{\partial z} + g\nabla_{z^*}\eta + \nabla_h \Phi'
$$

$$
= \boldsymbol{D}_{z^*,\boldsymbol{v}} + \boldsymbol{D}_{\perp,\boldsymbol{v}} + \mathcal{F}_{\boldsymbol{v}},
$$

$$
\frac{\partial \Phi'}{\partial z} = g\frac{\rho'}{\rho_c},
$$

$$
\frac{1}{H}\frac{\partial \eta}{\partial t} + \nabla_{z^*}(s^*\boldsymbol{v}) + \frac{\partial w}{\partial z^*} = s^*\mathcal{F},
$$

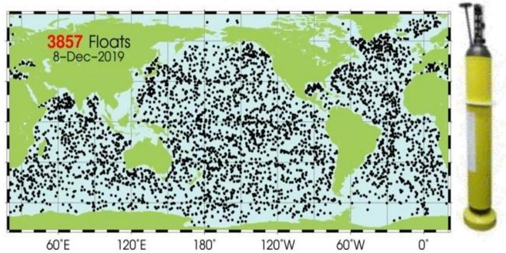
$$
\frac{\partial (s^*\theta)}{\partial t} + \nabla_{z^*}(s^*\theta\boldsymbol{v}_{\mathrm{res}}) + \frac{\partial (\theta w_{\mathrm{res}})}{\partial z^*}
$$

$$
= s^*(\mathcal{F}_\theta + D_{\sigma,\theta} + D_{\perp,\theta}),
$$

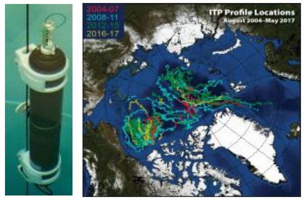
$$
\frac{\partial (s^*S)}{\partial t} + \nabla_{z^*}(s^*S\boldsymbol{v}_{\mathrm{res}}) + \frac{\partial (S w_{\mathrm{res}})}{\partial z^*}
$$

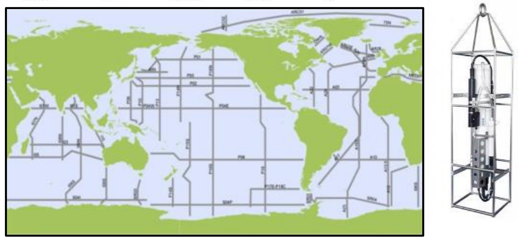
$$
= s^*(\mathcal{F}_S + D_{\sigma,S} + D_{\perp,S}),
$$

Argo Profiling Floats

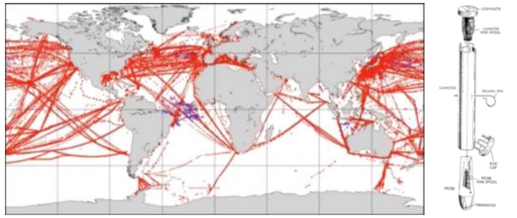


Ice-tethered profilers

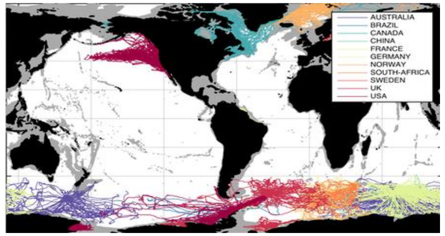




CTD
- *GO-SHIP*
- *WOCE*
- *others*



XBT



Instrumented marine mammals

Instrumented moorings

NASA’s ECCO Version 4: A global multi-decadal ocean and sea-ice reanalysis

Ocean model

Massachusetts Institute of Technology general circulation model (**MITgcm**) coupled ocean, sea-ice, ice-shelf model, and its **adjoint**, generated via automatic differentiation

Horizontal resolution

Nominally 1-degee with finer resolution at high latitudes

Vertical resolution

50 unequally-spaced z^* levels, dz =10 m at surface

Time window:

1992-2022

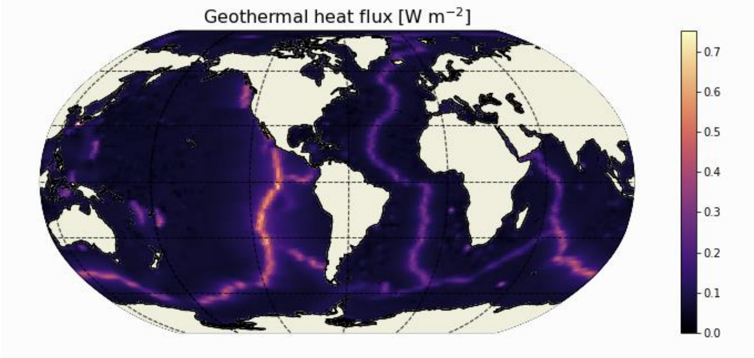
First-guess atmospheric state:

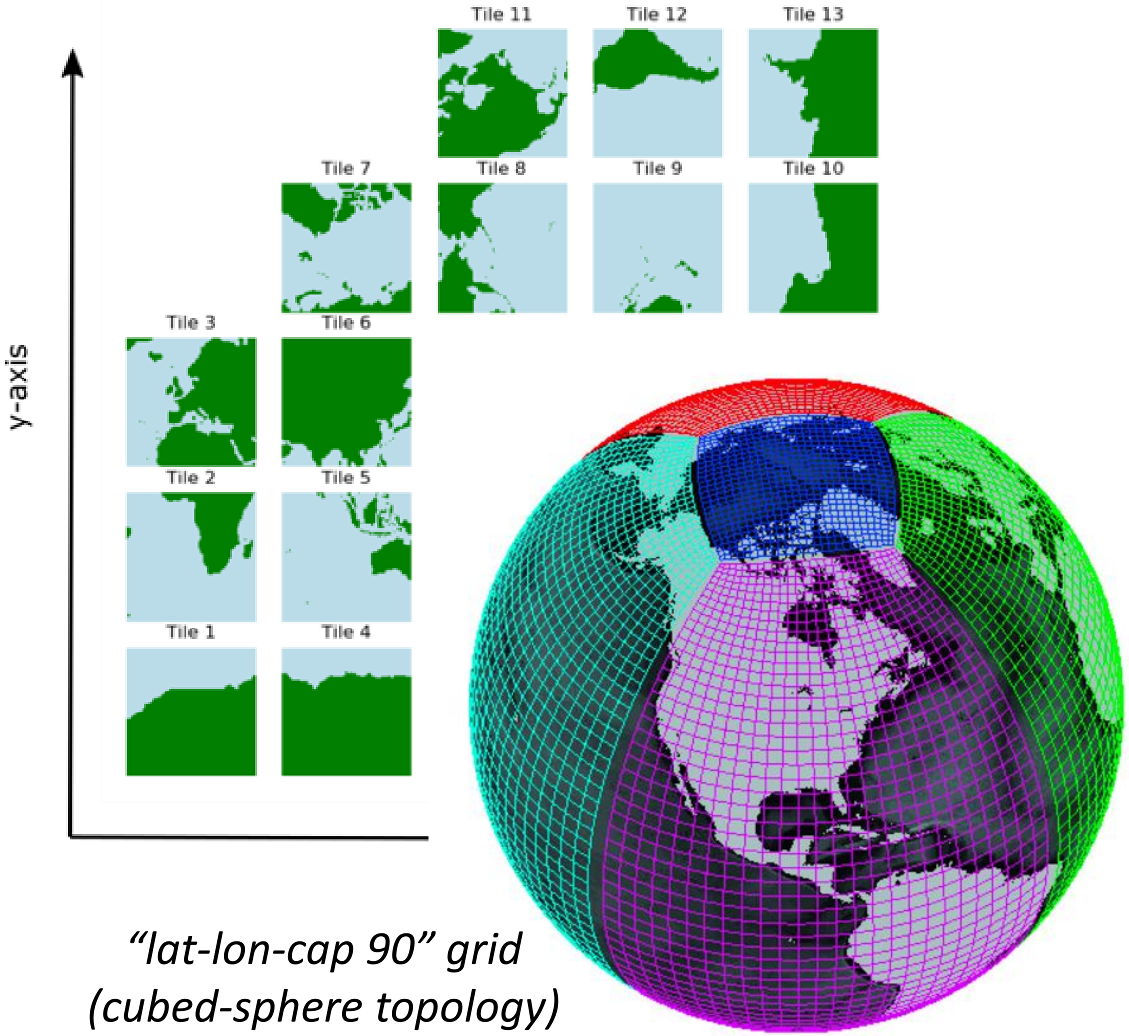
MERRA-2 from NASA GMAO (Gelaro et al., 2017)

Sub-ice shelf cavities:

Antarctica

Geothermal heating:





“lat-lon-cap 90” grid (cubed-sphere topology)

Challenges of "reanalysis" for climate

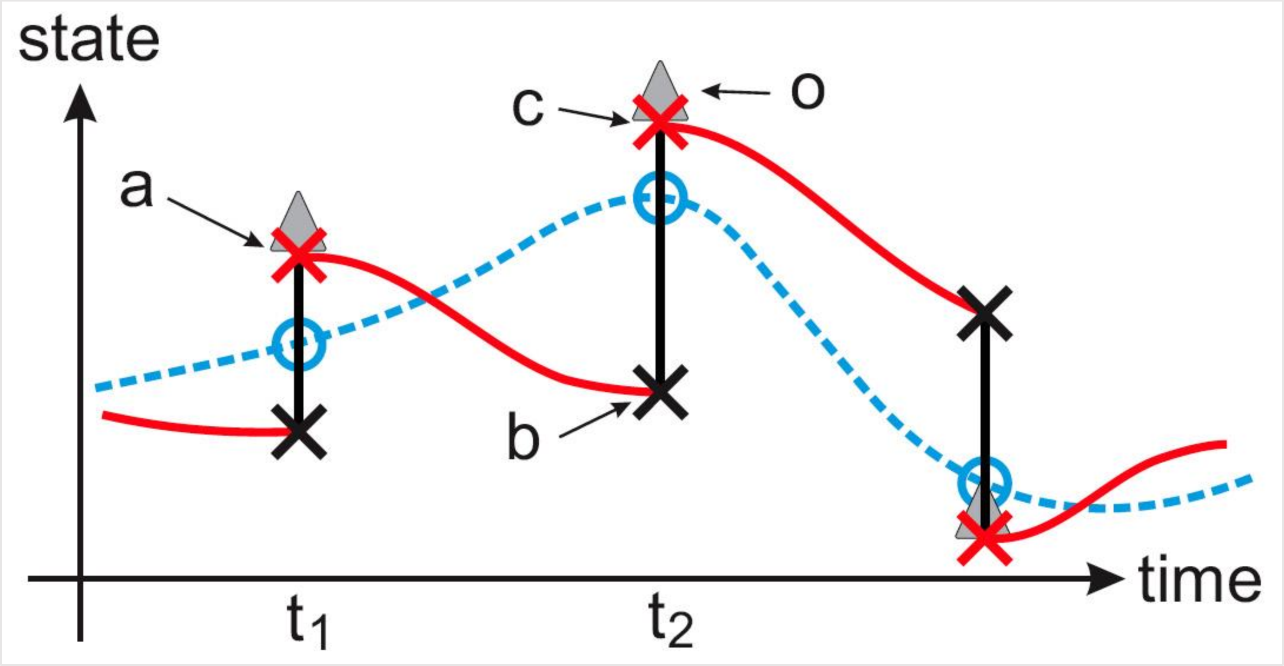
Smoothers vs. filters: dynamical & kinematical consistency

Numerical Weather Prediction (NWP) – a filtering problem

N. Wiener (1950):
Extrapolation, interpolation and smoothing of stationary time series.

- Relatively abundant data sampling of the 3-dim. atmosphere
- NWP targets optimal forecasting
  - ➔ find initial conditions which produce best possible forecast;
  - ➔ *dynamical consistency or property conservation* ***NOT required***

x : observation (data)
— : sequential assimilation trajectory
x : forecast at observation time
--- : state estimate trajectory
o : state estimate at observation time



Challenges of "reanalysis" for climate

Smoothers vs. filters: dynamical & kinematical consistency

Numerical Weather Prediction (NWP) – a filtering problem

- Relatively abundant data sampling of the 3-dim. atmosphere
- NWP targets optimal forecasting

  ➔ find initial conditions which produce best possible forecast;

  ➔ *dynamical consistency or property conservation* ***NOT required***

Ocean state estimation/reconstruction – a smoothing problem

- Sparse data sampling of the 3-D. ocea
- Understanding past & present state o

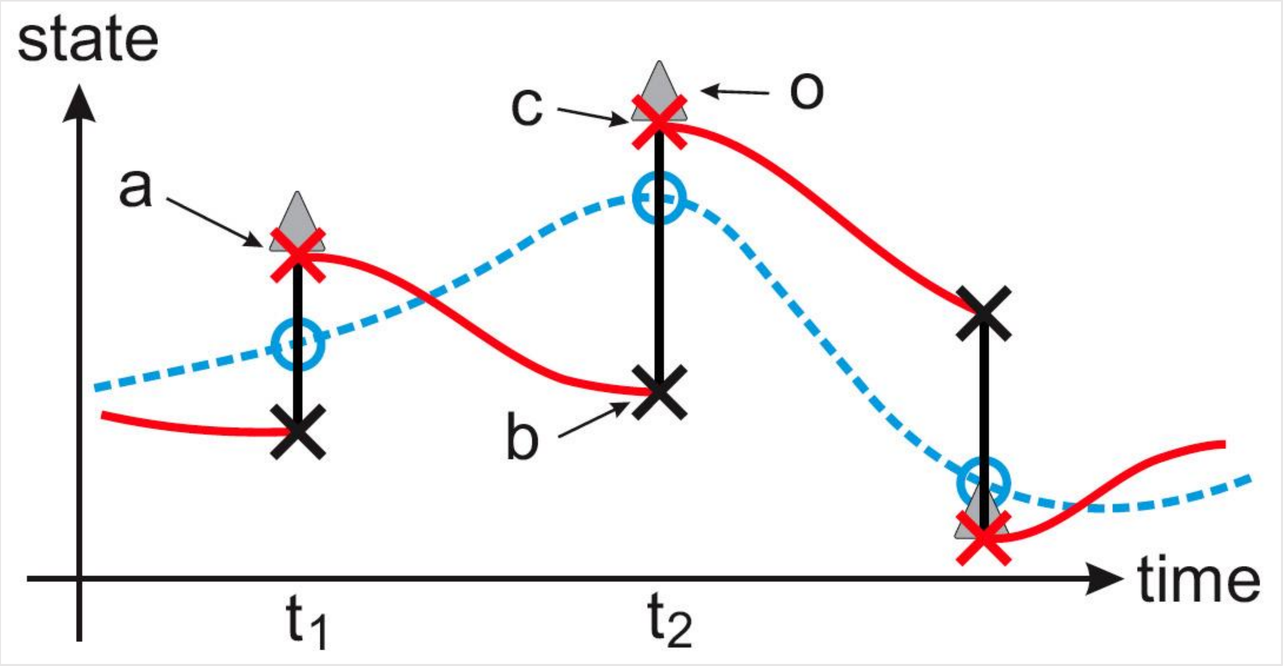
  the ocean is a major goal all by itself

  ➔ use observations in an optimal way

  ➔ *dynamic consistency & property conservation* ***ESSENTIAL for climate***

N. Wiener (1950):
Extrapolation, interpolation and smoothing of stationary time series.

x : observation (data)
— : sequential assimilation trajectory
x : forecast at observation time
--- : state estimate trajectory
o : state estimate at observation time



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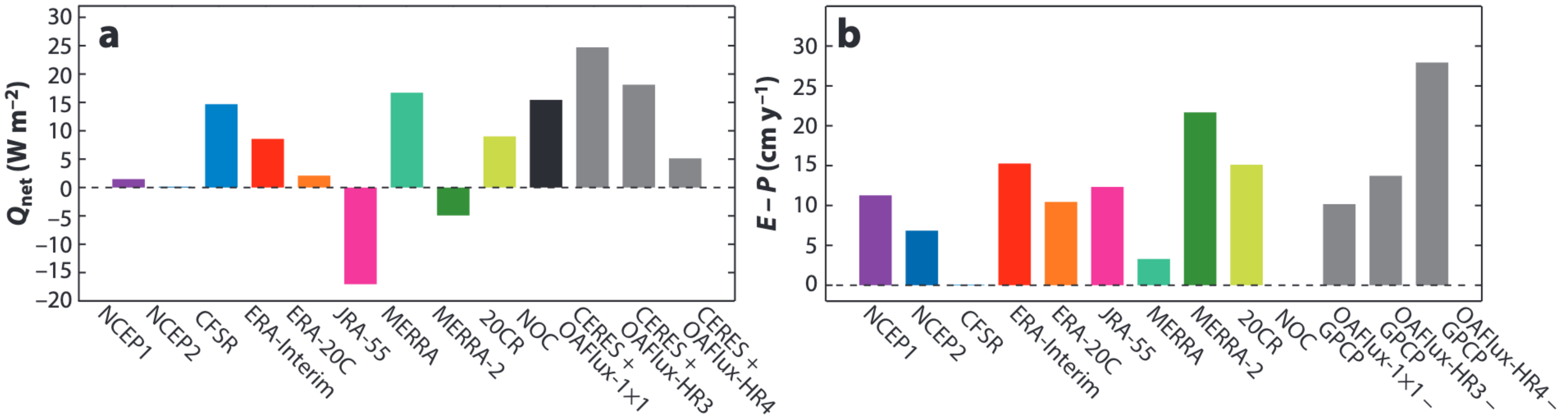
Applications of ocean *reconstructions / state estimates / "reanalyses"* for climate

Balancing the momentum, freshwater, and heat budgets

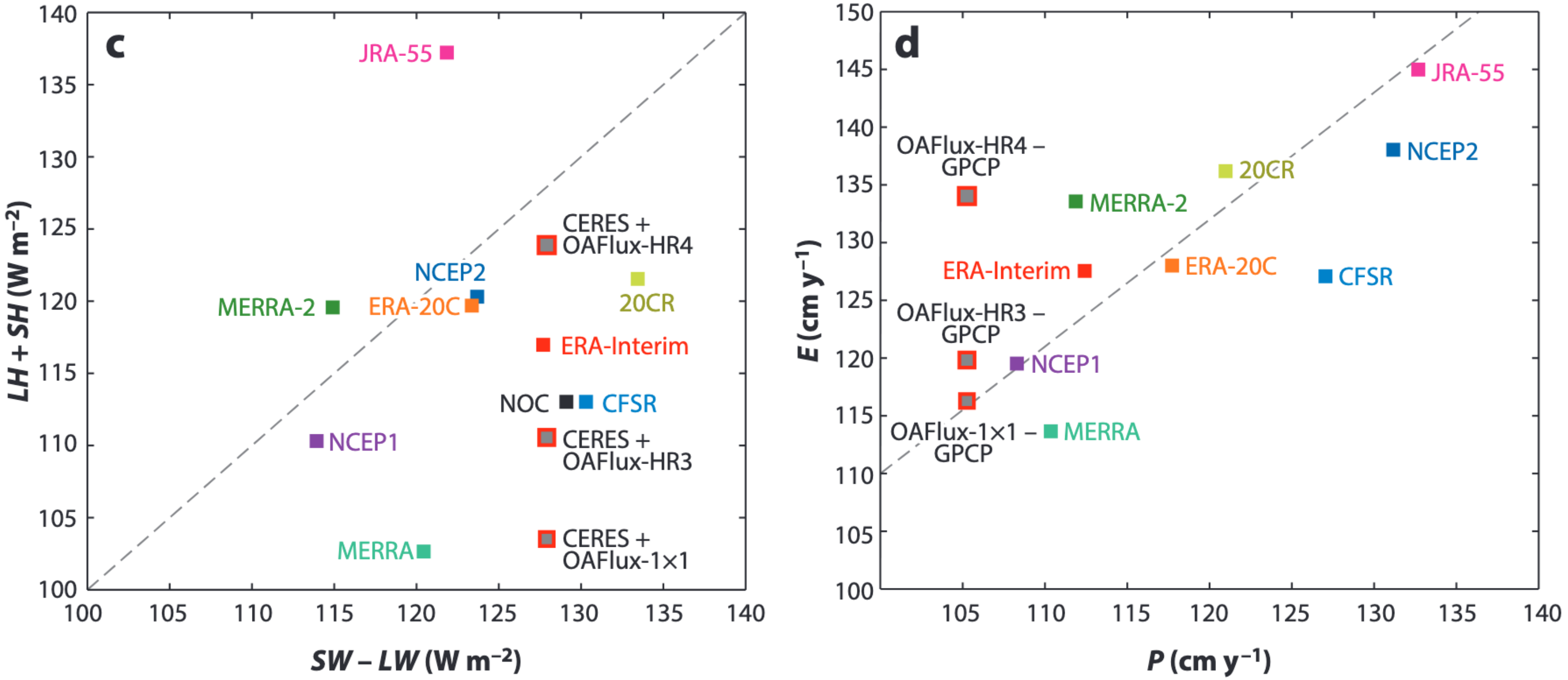
WMO OMM

Global net air-sea fluxes of heat (*EEI!*) and freshwater (*barystatic sea level!*)

Balancing the momentum, freshwater, and heat budgets



L. Yu, *Annu. Rev. Mar. Sci.* (2019)



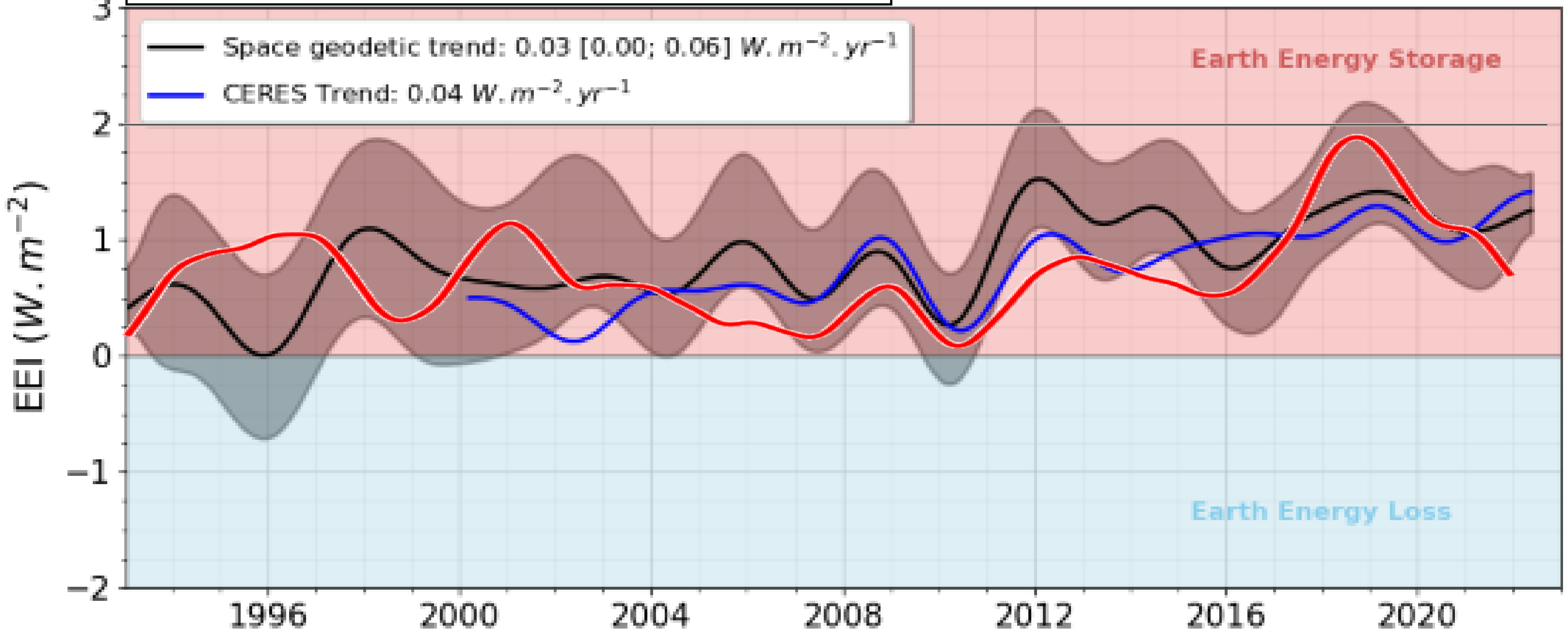
ECCO net air-sea heat flux & Earth Energy Imbalance

ECCO Earth Energy Imbalance

Mean: 0.79 W m^{-2}

Earth Energy Imbalance

Mean: 0.83 [0.66; 1.15] $W.m^{-2}$

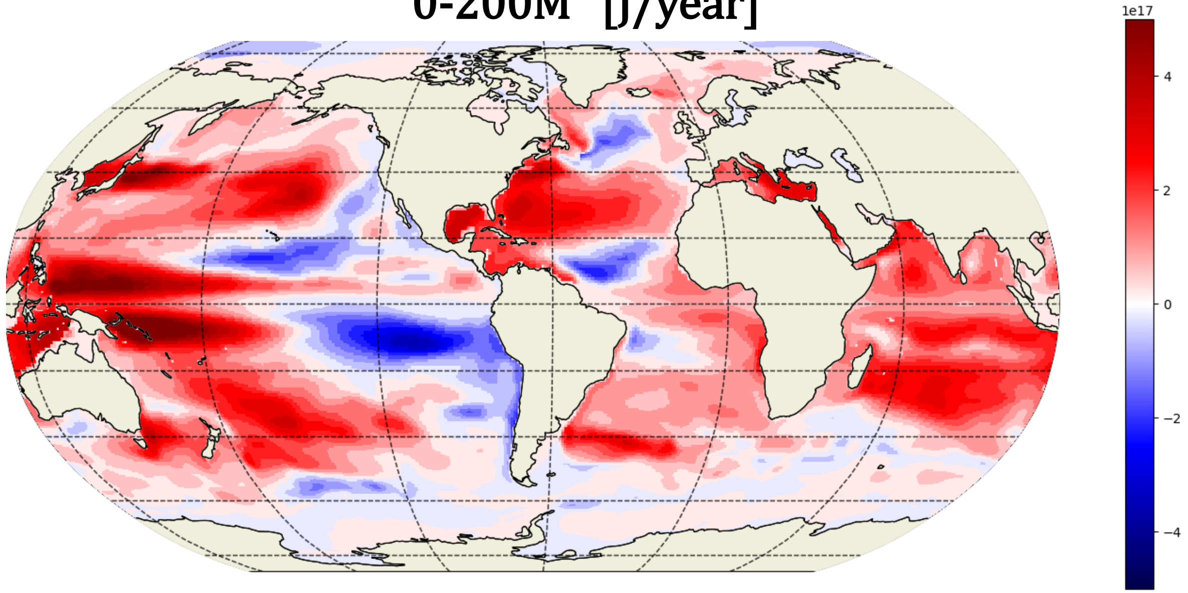


Period: 01/1993 - 05/2022
Confidence level at [5%; 95%]

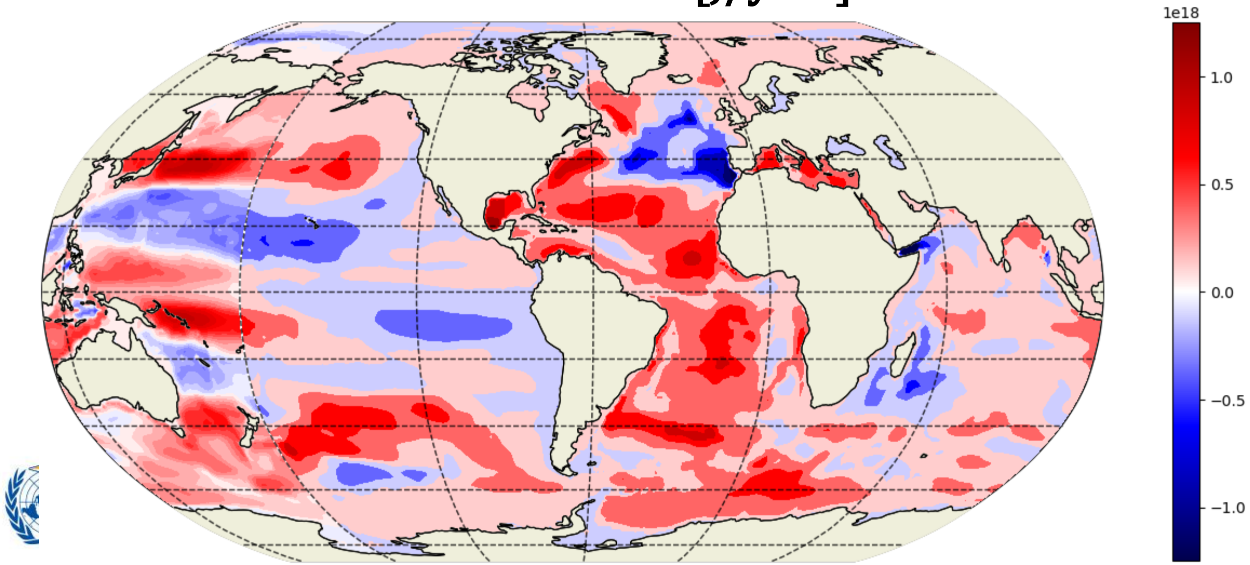
https://www.aviso.altimetry.fr/en/data/products/ocean-indicators-products/ocean-heat-content-and-earth-energy-imbalance/global-ocean-heat-content-change-and-earth-energy-imbalance.html

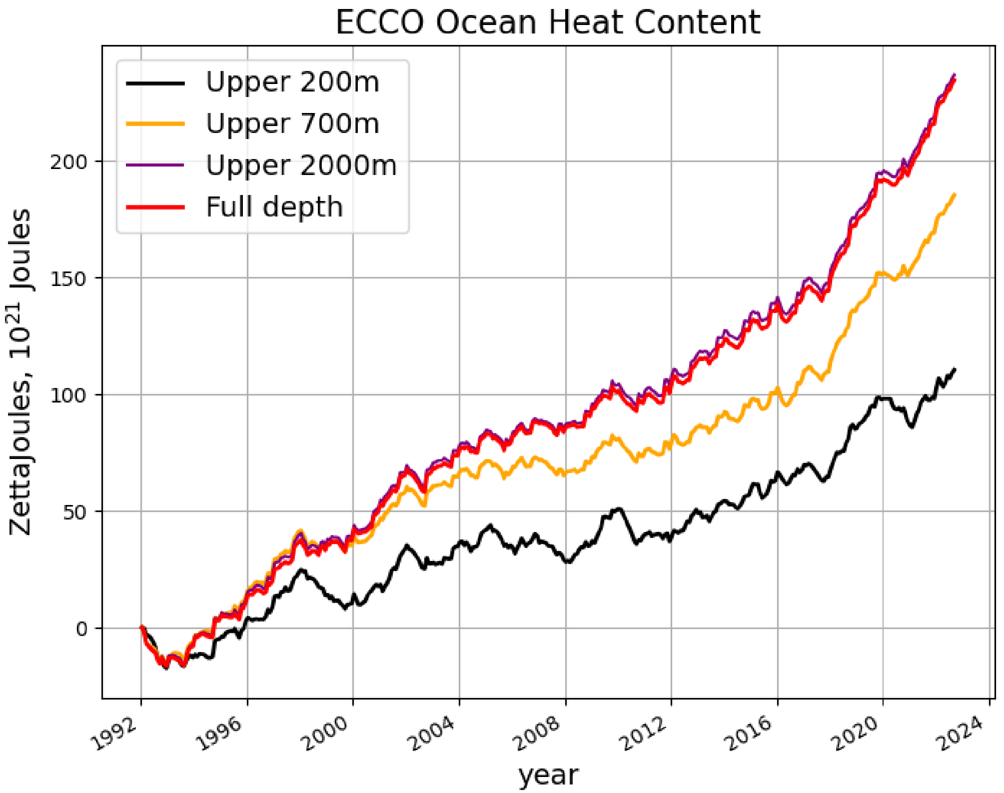
ECCO upper ocean and full-depth ocean heat content trends 1992-2022

0-200M [J/year]



FULL DEPTH [J/year]





1992-2022

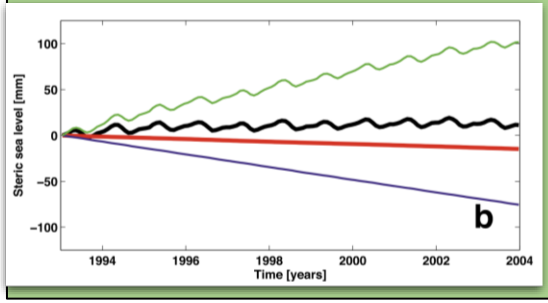
0 - 700 m : 0.56 Wm^{-2}
0 - 2000 m : 0.71 Wm^{-2}
0 - 6000 m : 0.70 Wm^{-2}

2006-2022

0 - 700 m : 0.62 Wm^{-2}
0 - 2000 m : 0.77 Wm^{-2}
0 - 6000 m : 0.81 Wm^{-2}

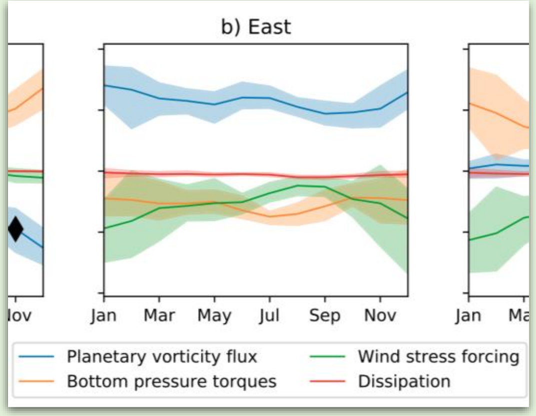
(Fenty et al.)

Scientific analyses involving detailed budget calculations



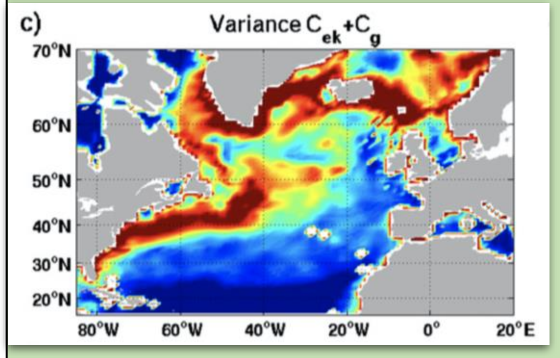
Mechanisms of global-mean steric sea level change

(Piecuch & Ponte 2014)



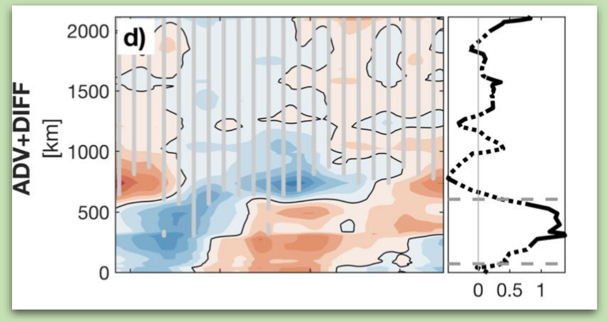
Barotropic vorticity budget in the subtropical N. Atlantic

(Le Bras et al. 2019)



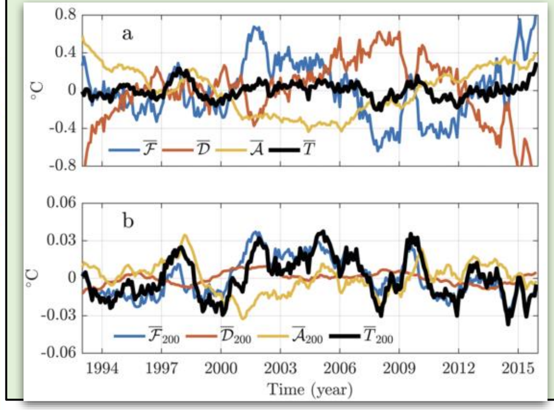
Upper ocean heat content variability in the N. Atlantic

(Buckley et al. 2014, 2015)



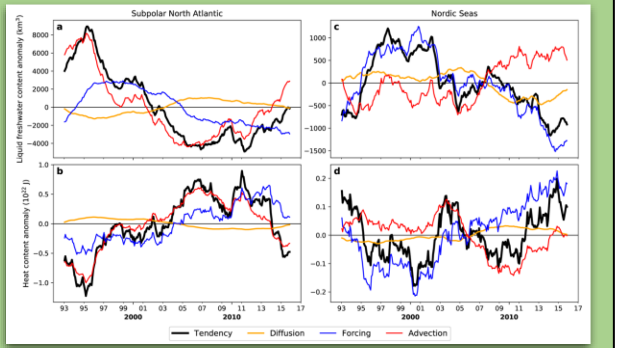
Mechanisms underlying recent Arctic amplification

(Asbjørnsen et al. 2020)



Mechanisms controlling global mean SST variability

(Ponte & Piecuch 2018)



Heat & freshwater budgets in the SPG & Nordic Seas

(Tesdal & Haine 2020)

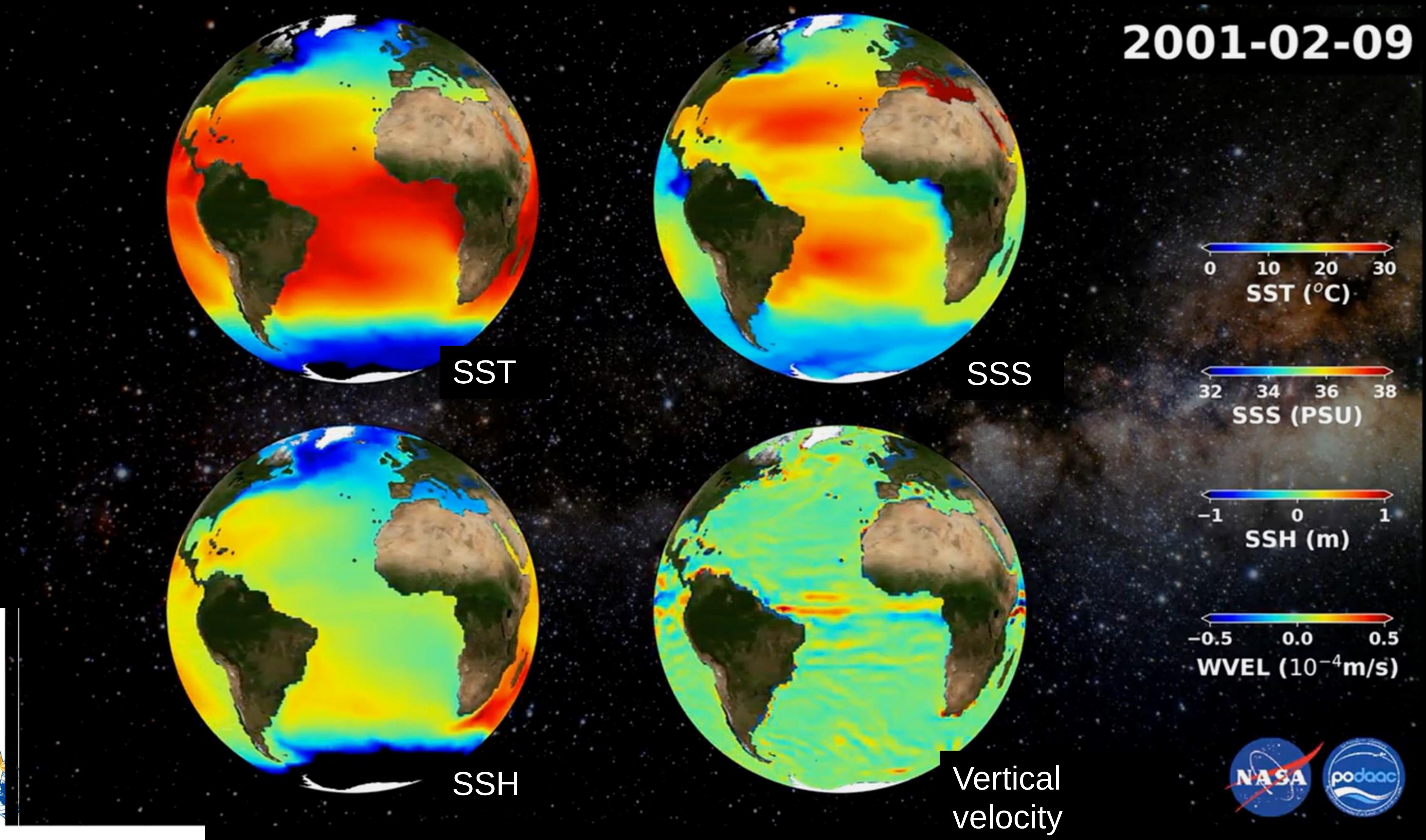
Accessing the data

Estimating the Circulation and Climate of the Ocean (ECCO)

Mission Objectives

NASA's Estimating the Circulation and Climate of the Ocean (ECCO) project supports climate research by providing the scientific community with the best possible multidecadal reconstructions of Earth's time-evolving full-depth ocean, sea-ice, and atmospheric surface states and their associated fluxes.

Select fields from the latest 1-degree ECCO Central Estimate http://www-ecco-group.org



SST

SSS

SSH

Vertical velocity

Home » Dataset Discovery

ECCO Sea Surface Height - Monthly Mean 0.5 Degree (Version 4 Release 4b)
(ECCO_L4_SSH_05DEG_MONTHLY_V4R4B)

Version	V4r4b
Processing Level	4
Start/Stop Date	1992-Jan-01 to 2018-Jan-01
Short Name	ECCO_L4_SSH_05DEG_MONTHLY_V4R4B
Description	This dataset contains monthly-averaged dynamic sea surface height interpolated to a regular 0.5-degree grid from the ECCO Version 4b revision 4 (V4r4b) ocean and sea-ice state estimate. V4r4b is an errata for ECCO Version 4, Release 4 (V4r4). Estimating the Circulation and Climate of the Ocean (ECCO) ocean and sea-ice state estimates are dynamically and kinematically-consistent reconstructions of the three-dimensional, time-evolving ocean, sea-ice, and surface atmospheric states. ECCO V4r4b is a free-running solution of the 1-degree global configuration of the MIT general circulation model (MITgcm) that has been fit to observations in a least-squares sense. Observational data constraints used in V4r4b include sea surface height (SSH) from satellite altimeters [ERS-1/2, TOPEX/Poseidon, GFO, ENVISAT, Jason-1,2,3, CryoSat-2, and SARAL/AltiKa]; sea

Status: COMPLETE

Short Name:
ECCO_L4_SSH_05DEG_MONTHLY_V4R4B

Collection Concept ID:
C2129189405-POCLOUD

Spatial Coverage:

N:	90°	**S:**	-90°
E:	180°	**W:**	-180°

Access:
- Search Granules
- Browse Granule Listing

Capabilities:

NASA's EARTHDATA Open Science Cloud

ECCO Version 4: estimated fields provided to the community

Ocean/Sea-Ice State & Transports

- ***Ocean state:***
  - Temperature (T_0)
  - Salinity (S_0)
  - Velocity/current (*u,v,w*)
  - Sea surface height
  - Density
  - Ocean bottom pressure anomaly
- ***Sea-ice/snow state:***
  - concentration,
  - ice and snow thickness
  - 2-D rift velocity (2-D)
- **3D transports of**
  - volume, heat, salt, momentum
- ***2D transports of***
  - sea-ice and snow volume

Atmosphere State and Air-Sea Fluxes

- ***Atmospheric state:***
  - surface air temperature
  - precipitation
  - specific humidity
  - wind speed & wind stress
  - downwelling short and long-wave radiative fluxes
- ***Air–sea ice–ocean fluxes***
  - heat
  - water (P-E+R)
  - Wind stress (momentum)

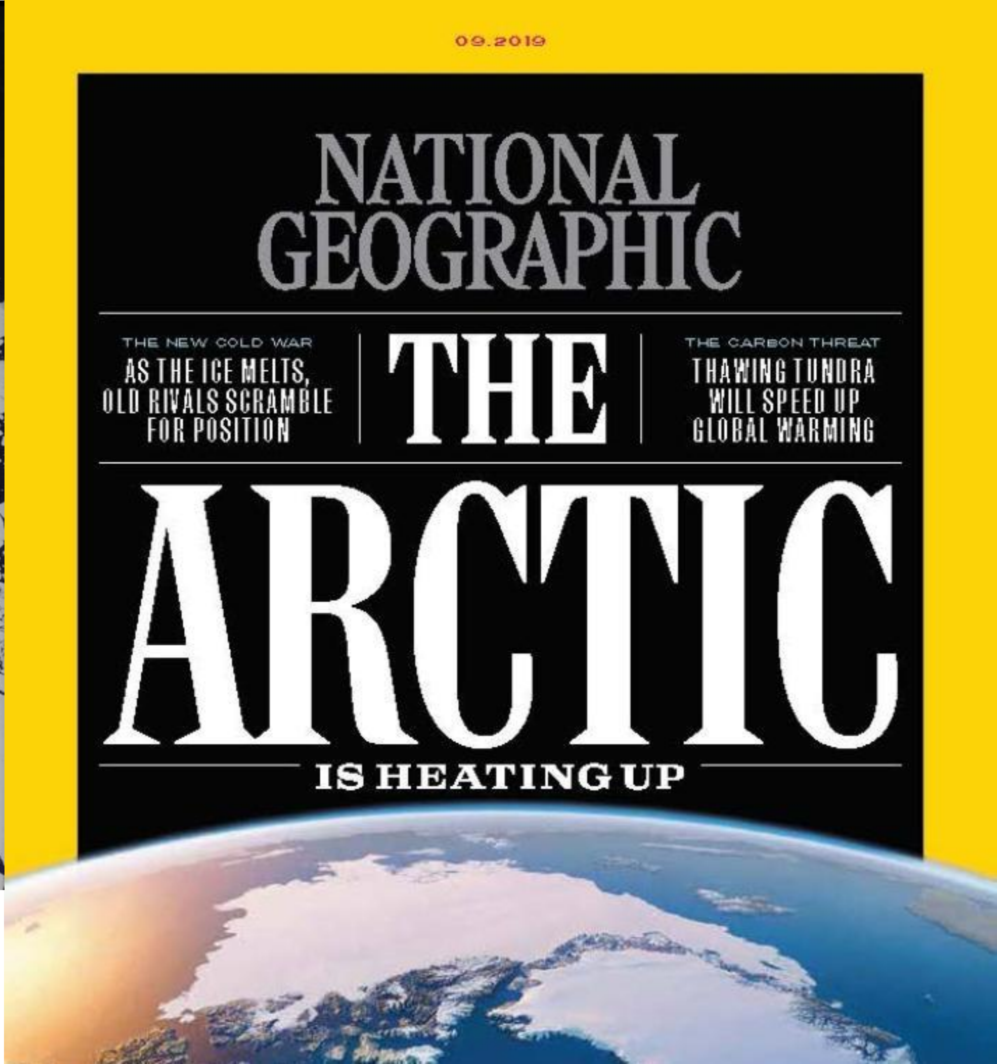
Subgrid-scale mixing parameters

- *3D Gent-McWilliams and Redi mixing κ*
- *3D vertical diffusivity*

RED : *model control parameters*

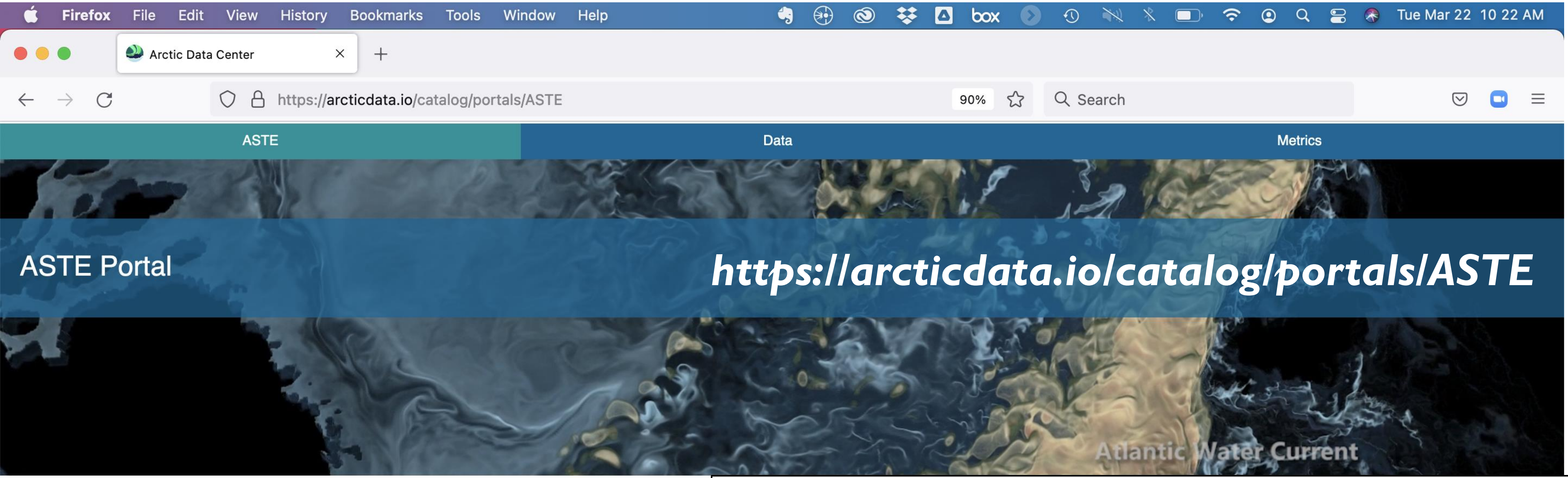
Initial T_0 and S_0 are model control parameters

A regional focus: the coupled Arctic ocean-sea ice system



WMO OMM

The Arctic Subpolar Gyre State Estimate (ASTE) serving the community via NSF's Arctic Data Center (*arcticdata.io*)



ASTE Portal

https://arcticdata.io/catalog/portals/ASTE

- Project Overview
- Product Synopsis

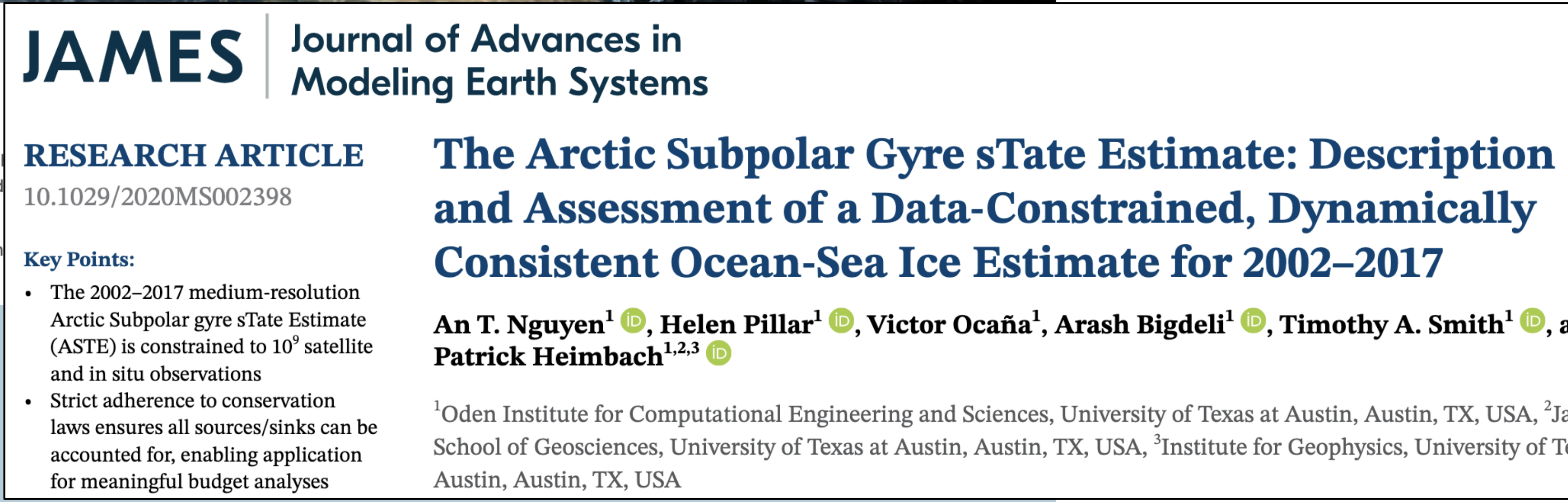
Project Overview

The Arctic Subpolar gyre sTate Estimate (ASTE) i
subpolar North Atlantic, using the adjoint-based d
detail in Nguyen et al., JAMES, 2021.

As part of the project, which received main fundin
Exploring the Arctic Ocean.

NSF Arctic Data Center

NCEAS UCSB DataONE NOAA NSF



JAMES Journal of Advances in Modeling Earth Systems

RESEARCH ARTICLE

10.1029/2020MS002398

Key Points:

- The 2002–2017 medium-resolution Arctic Subpolar gyre sTate Estimate (ASTE) is constrained to 10^9 satellite and in situ observations
- Strict adherence to conservation laws ensures all sources/sinks can be accounted for, enabling application for meaningful budget analyses

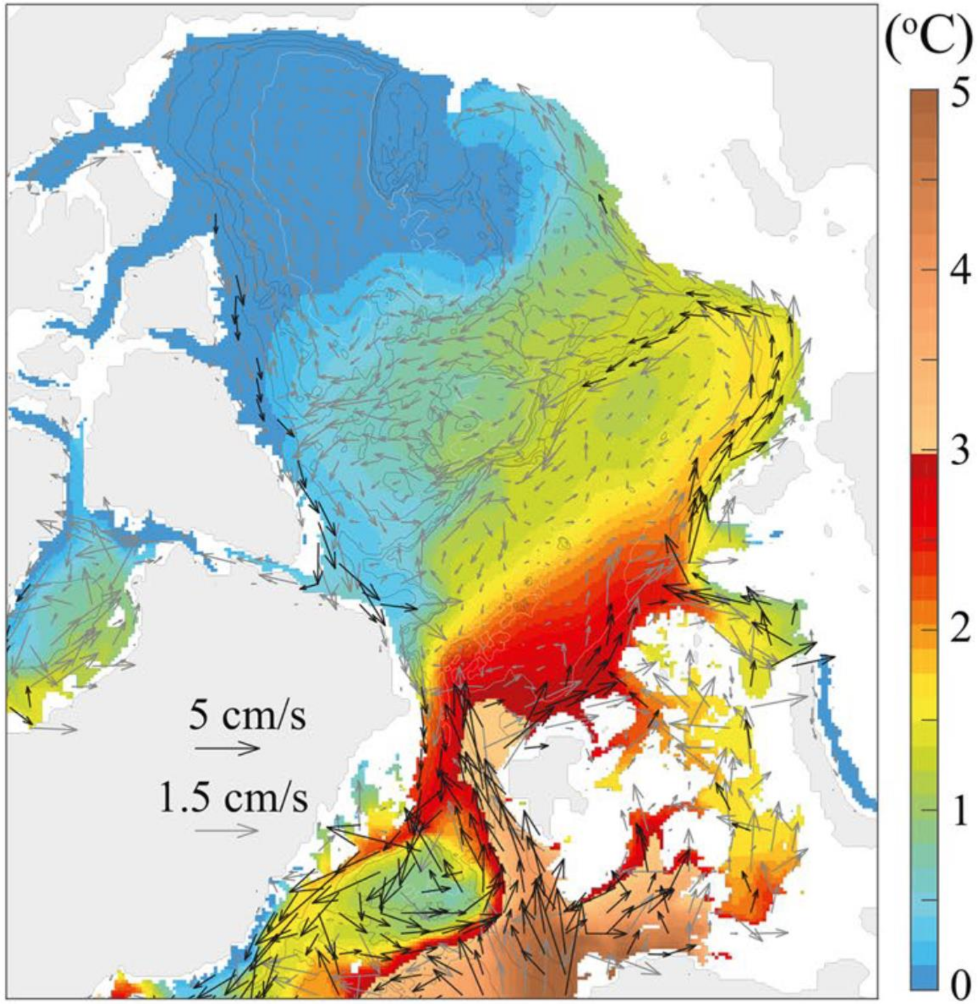
The Arctic Subpolar Gyre sTate Estimate: Description and Assessment of a Data-Constrained, Dynamically Consistent Ocean-Sea Ice Estimate for 2002–2017

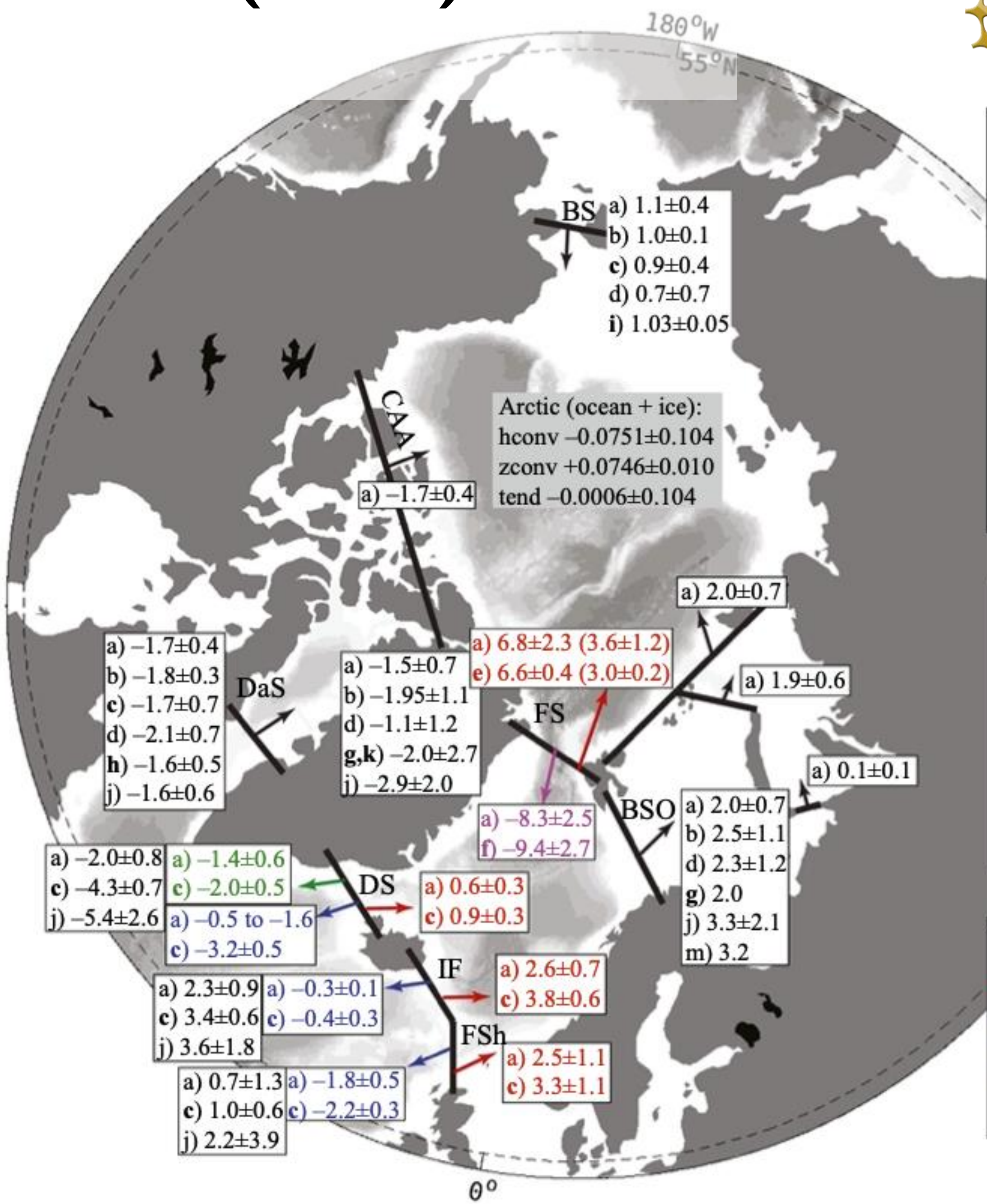
An T. Nguyen[1], Helen Pillar[1], Victor Ocaña[1], Arash Bigdeli[1], Timothy A. Smith[1], a
Patrick Heimbach[1,2,3]

[1]Oden Institute for Computational Engineering and Sciences, University of Texas at Austin, Austin, TX, USA, [2]Ja
School of Geosciences, University of Texas at Austin, Austin, TX, USA, [3]Institute for Geophysics, University of T
Austin, Austin, TX, USA

Arctic Subpolar gyre sTate Estimate (ASTE)

Nguyen et al., JAMES (2021)





Reference

a: ASTE R1 (2006-2017)
b: Ilikak 2016 (1978-2007)
c: Østerhus 2019 (1993-2015)
d: Tsubouchi 2018 (09/2005-08/2006)
e: Beszczynska 2012 (1997-2010)
f: deSteur 2014 (1997-2009)
g: Schauer 2008 (1997-2007)
h: Curry 2014 (2004-2010)
i: Woodgate 2018 (2003-2015)
j: Tesdal 2020 (1992-2015)
k: Marnela 2016 (1999-2010)
l: Rossby 2018 (2009-2016)
m: Smedsrud 2010 (1997-2007)

Gateway

BS: Bering Strait
FS: Fram Strait
CAA: Canada Arctic Archipelago
BSO: Barents Sea Opening
DaS: Davis Strait
DS: Denmark Strait
IF: Iceland-Faroe
FSh: Faroe-Shetland

Transport component

→ Inflow
→ Surface outflow
→ Dense outflow
→ Modified Water outflow
→ Net

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Future plans for ECCO

- Bring ocean climate state estimates to near-realtime
- Extend back to 1980 (start of satellite SST and sea ice cover)
- Increase horizontal resolution (target 1/6°)
- Improved representation of cryospheric processes and data constraints
- Improved uncertainty estimates
- Coupling to biogeochemical cycles

BAMS

Meeting Summary

See also:
US CLIVAR Workshop Summary

Road Map for the Next Decade of Earth System Reanalysis in the United States

Sergey Frolov, Cécile S. Rousseaux, Tom Auligne, Dick Dee, Ron Gelaro, Patrick Heimbach, Isla Simpson, and Laura Slivinski

BAMS, 2023, *https://doi.org/10.1175/BAMS-D-23-0011.1*